An Experimental Investigation on Damping with Multilayered Aluminium Riveted and Cantilevered Structure

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Abstract— The present investigation highlights the effect of interfacial slip on the damping of layered cantilever beams jointed with rivets undergoing free vibration. A lot of experiments have been conducted on a number of specimens with connecting rivet of various diameters, length and thickness to study its effect on the damping capacity of the layered and jointed structures and to establish the authenticity of the theory. Intensity of interface pressure, diameter of the connected rivet, length and thickness of beam, number of layers, kinematic coefficient of friction at the interfaces and frequency and amplitude of excitation are found to play a major role on the damping capacity of such structures. This design concept of using layered structures with riveted joints can be effectively utilized in trusses and frames, aircraft and aerospace structures, bridges, machine members, robots and many other applications where higher damping is required. Riveted joints are often used to fabricate assembled structures in machine tools, automotive and many such industries requiring high damping. For a particular specification of the beam with thickness ratio 1.0, overall beam thickness 6 mm, and diameter of rivet 10 mm excited at 0.5 mm. Due to the incorporation of joints, it is estimated that the damping capacity increases approximately by 125 to 130 % , whereas their stiffness decreases by 15% to 22% only. When the rivet diameter Increases from 8 to 10 mm logarithmic decrement Increases by 13.26%.

Key words: Slip damping, Amplitude, Multiple interfaces, Dynamic loading, Riveted joint

I. Introduction

Problems involving vibration occur in many areas of mechanical, civil and aerospace engineering. So as a structural member there is a critical need for development of reliable and practical mathematical models to predict the dynamic behaviour of such built-up structures to control the vibration of structures at a desirable level. Engineering structures are generally fabricated using a variety of connections such as bolted, riveted, welded and bonded joints etc. Usually, such structures possess both low structural weight and damping. Unwanted vibrations with high amplitude can be the cause of the fatigue failures in machine elements and the reduction of their working life. This situation calls for use of additional measures to improve the damping characteristics by dissipating more energy. The dynamics of mechanical joints is a topic of special interest due to their strong influence in the performance of the structure. Joints are inherently present in the assembled structures which con- tribute significantly to the slip damping in most of the fabricated structures. Further, the inclusion of these joints plays a significant role in the overall system behaviour, particularly the damping level of the structures. Joints have a great potential for reducing the vibration levels of a structure thereby attracting the interest of many researchers. The mechanical engineers are concerned of energy such as heat. Dissipation of energy takes with many unwanted vibrations in mechanical devices and replace at any time that the system vibrates.

In an earlier attempt, theory of structural damping in a built-up beam have been investigated by Pian and Hallowell [13] who considered a beam fabricated in to two parts and connected together by riveted cover plates. Goodman and Klumpp [12] on the other hand examined the energy dissipation by slip at the interfaces of a laminated beam.W. Chen, X. Deng [10] give the concept of Structural damping caused by micro-slip along frictional interfaces by using the finite element method. Later O. Damisa and V.O.S. Olunloyo [8] had performed their experiment on dynamic analysis of slip damping in clamped layered beams with non-uniform pressure distribution at the interface. Before attempting this experiment most analyses of the mechanism assume an environment of uniform pressure at the interface, experiments to date have confirmed that this is rarely the case. Their attempts to relax the restriction of uniform interface pressure.

With the introduction of composite materials and the possible beneficial effects it can have on slip damping, several authors have revisited the problem of layered or jointed structures subjected to uniform pressure distribution. In this regard, Nanda [9] studied the effect of structural members under controlled dynamic slip while Nanda and Behera examined the problem of slip damping of jointed structures with connection bolts as found in machine structures [11]. Nanda and Singh[1,5,6] went further to studying the distribution pattern of the interface pressure as well as the damping capacity of such layered and jointed structures by carrying out both numerical analysis and experiments to ascertain the effects of a number of layers, diameter of bolts and use of washers. After considering the bolted joint they had Identify the mechanism of damping in layered and welded structures. Their work is further extended by consideration of multi-layered welded aluminium and mild steel beams respectively for dynamic analysis of damping mechanism.

A little amount of work has been reported till date on the damping capacity of riveted structures. The present work outlines the basic formulation for the slip damping mechanism in layered and riveted structures. In the present investigation, damping capacity of layered and jointed structures is to be evaluated from analytical expressions developed in the investigation and compared experimentally for aluminium cantilever beams under different - different conditions of excitation in order to establish the accuracy of the theory developed.

A. Riveted Joint

A rivet is a short cylindrical bar with a head integral with it. The set head is made before hand on the body of the rivet by upsetting. The second, called the closing head, is formed during riveting. A riveted joint is made by inserting rivets into holes in the elements to be connected. A joint holding two or more elements together by the use of rivets are called riveted joints.

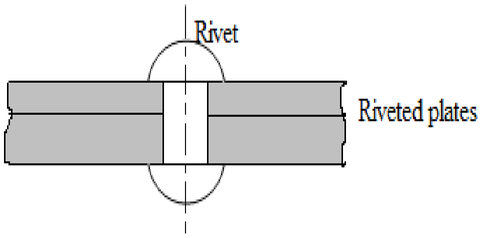

Fig. 1: Riveted joint

II. THEORETICAL ANALYSIS

This chapter gives a detailed description of the theoretical analysis by classical energy approach for determining the damping capacity in layered and jointed cantilever beams with riveted joints. A cantilever beam model representing a continuous system based on the Euler-Bernoulli beam theory has been used for deriving the necessary formulations.

Most structural problems are studied based on the assumption that the structure to be analysed is either linear or nonlinear. In linear systems, the excitation and response are linearly related and their relationship is given by a linear plot as shown in Fig.2

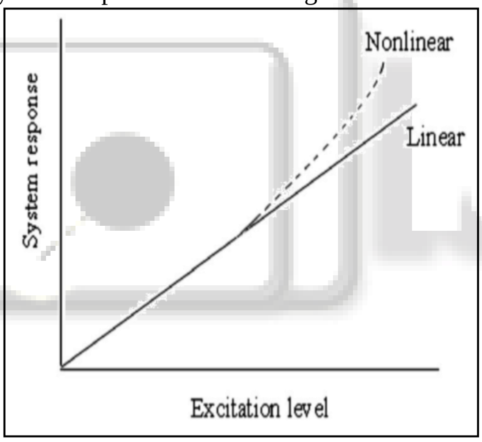

Fig. 2: Comparison of linear and nonlinear system

Working with linear models is easier from both an analytical and experimental point of view. For beams undergoing small displacements, linear beam theory is used to calculate the natural frequencies, mode shapes and the response for a given excitation. It is very clear from Fig.2 that the linear and nonlinear systems agree well at small values of excitation, while they deviate at higher levels. The linear vibration theory is used when the beam is vibrated at small amplitudes and lower modes of vibration. The present investigation mainly focuses on the study of damping of jointed Cantilever beams at lower excitation levels which can be considered as linear.

A. Dynamic Equations of Free Transverse Vibration of a Cantilever Beam

In formulating the dynamic equations, Euler-Bernoulli beam theory is used on the assumptions that the rotation of the differential element is negligible compared to translation and the angular distortion due to shear is small in relation to bending deformation. The beam vibration is governed by partial differential equations in terms of spatial variable x and time variable t. Thus, the governing differential equation for the free transverse vibration is given by;

$$\frac{c^2 \partial y(x,t)}{\partial x} = -\frac{\partial^2 y(x,t)}{\partial t} \qquad (1)$$

Where $c = \sqrt{\frac{EI}{\rho A}}$ and E, I, ρ and A are modulus of elasticity, second moment of area of the beam, mass density and cross-sectional area, respectively. The free vibration given by equation (1) contains four spatial derivatives and hence requires four boundary conditions for getting a solution. Cantilever beam undergoing free vibration with transverse displacement y(x, t).The presence of two time derivatives again requires two initial conditions, one for the displacement and another for velocity. The above equation is solved using the technique of separation of variables. In this method, the displacement *y(x , t)*is written as the product of two functions, one depending only on x and the other depending only on t. Vibration in cantilever beam is expressed as;

$$y(x, t) = Y(x)\, f(t) \qquad (2)$$

Where Y(x)and f(t) are the space and time function, respectively. f(t) is given by

$$f(t) = A \cos \omega_n t + B \sin \omega_n t \qquad (3)$$

Where A and B are constants &$\omega_n$is the natural frequency.

Space function Y(x) is given by;

$$Y(x) = \frac{(\cos h\lambda l - \cos \lambda l)(\sin \lambda l + \sin h\lambda l) + (\sin \lambda l - \sin h\lambda l)(\cos \lambda l + \cos h\lambda l)}{(\cos \lambda l + \cos h\lambda l)} \qquad (4)$$

Putting equations (3) and (4) in (2) we get;

$$y(x, t) = Y(x)(A \cos \omega_n t + B \sin \omega_n t) \qquad (5)$$

Putting the boundary conditions given as;

$$y(l,0) = Y_0$$

$$\frac{dy(l,0)}{dx} = 0$$

In equation (4) and simplifying we get;

$$A = \frac{y_0}{Y(l)}$$

$$B=0$$

By inserting the values of *A* and *B* in equation (5) we get the transverse deflection of the cantilever beam at the free end as;

$$y(x,t) = Y(x)\left[\frac{y_0}{Y(l)} \cos \omega_n t\right] \qquad (6)$$

B. Evaluation of Relative Dynamic Slip

It is assumed that each jointed cantilever beam being vibrated are equal bending stiffness with the same bending condition. Moreover, each layer of the beam shows no extension of the neutral axis and no deformation of the cross-section. When the jointed cantilever beam is given an initial excitation at the free end, the contacting surfaces undergo relative motion called micro-slip. This relative displacement *u(x, t)* at any distance from the fixed end in the absence of friction is equal to the sum of $\Delta u_1$and Δu_2 as shown in Fig.3

$$u(x,t) = \Delta u_1 + \Delta u_2 = 2h \tan[\frac{\partial y(x,t)}{\partial x}] \qquad (7)$$

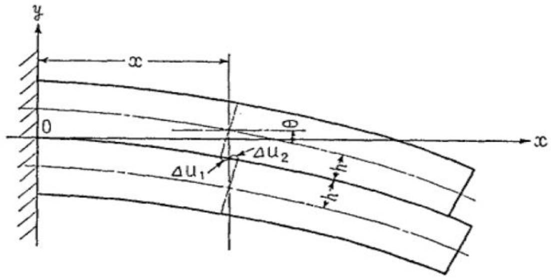

Fig. 3: Mechanism of the horizontal displacement

However, the actual relative dynamic slip $[u_r(x,t)]$ at the interfaces in the presence of friction during the vibration will be less and is found out by subtracting the elastic recovery part of the relative displacement from *u(x, t)* and is rewritten as;

$$u(x,t) = \alpha u(x,t) = 2h\alpha \tan\left[\frac{\partial y(x,t)}{\partial x}\right] \quad (8)$$

Where, α and $y(x,t)$is the dynamic slip ratio and transverse deflection of the beam.

C. Determination of Logarithmic Decrement

For a lightly damped linear system, the damping capacity of a jointed beam is usually determined from the logarithmic decrement method. Logarithmic decrement (δ), a measure of damping capacity, is defined as the natural logarithm of the ratio of two consecutive amplitudes in a given cycle. This approach is generally used to estimate the damping from the experiments in which the decaying amplitude is recorded from the time history plot. For the theoretical evaluation of damping, the energy approach is popular because the logarithmic decrement is fundamentally equal to the energy loss per cycle of vibration. The logarithmic decrement depends on both the energy stored$(E_n)$and energy loss(E_{loss})in a system during one cycle of vibration. Thus, the logarithmic decrement is expressed as;

$$\delta = \frac{1}{2}(E_{loss} - E_n) \quad (9)$$

This is the generalized expression for numerical evaluation of logarithmic decrement for two layered beams of any thickness.

$$\delta = \frac{\mu N\alpha(h_1-h_2)X\lambda}{ky(l,0)} \quad (10)$$

When the thickness of each layer of the beam is equal, i.e., $2h_1 = 2h_2 (h_1 = h_2)$,the above expression is modified to;

$$\delta = \frac{\mu N\alpha h\lambda X}{ky(l,0)} \quad (11)$$

Moreover, this can be extended to cantilever beams having multi-number of layers of equal thickness. The use of more number of layers increases the number of interfaces and hence the energy losses, thereby increasing the logarithmic decrement of a multi-layered beam. If '*m*' number of layers is used to construct a jointed beam, the number of interfacial layers is always (*m*-1) and therefore, the logarithmic decrement for such a multi-layered beam is found out modifying expression 11 as;

$$\delta = \frac{2(m-1)\mu N\alpha hX\lambda}{ky(l,0)} \quad (12)$$

D. Pressure Distribution at the Jointed Interfaces

A layered and jointed construction is made by using the rivet that holds the plates together at the interface. At the interface of the member slip is occurring during vibration. In the presence of dynamic slip, profile of interface pressure distribution plays a significant role to dissipate vibration energy.

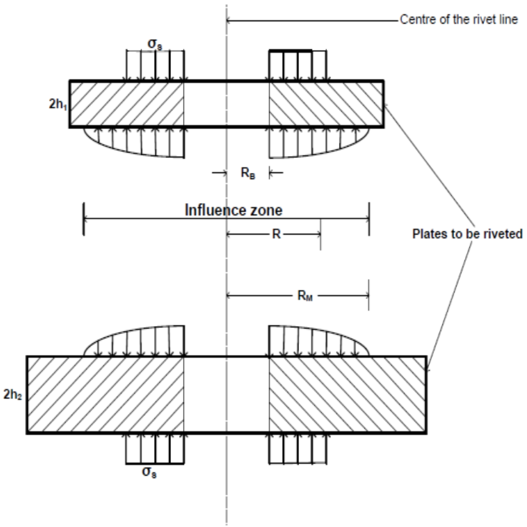

Fig. 4: Free body diagram of a riveted joint showing the influence zone.

As showing in the figure 4, the contact pressure at the jointed interface is non uniform in nature. Pressure being maximum at the rivet hole and decreases with the distance away from the rivet. This allow localized slipping at the interface while the overall joint remains locked.

E. Determination of Pressure Distribution at the Interfaces

The interface pressure distribution under each rivet in a non-dimensional polynomial for layered and jointed structures is assumed as;

$$\frac{p}{\sigma_s} = C_1\left(\frac{R}{R_B}\right)^{10} + C_2\left(\frac{R}{R_B}\right)^{8} + C_3\left(\frac{R}{R_B}\right)^{6} + C_4\left(\frac{R}{R_B}\right)^{4} + C_5\left(\frac{R}{R_B}\right)^{2} + C_6 \quad (13)$$

structure due to riveting, any radius within the influencing zone and radius of the connecting rivet, respectively and constants $C_1$to $C_6$are the polynomial. Where p,σ_s, R and R_B are the interface pressure, surface stress on the layered and jointed.

F. Analysis of Energy Dissipation on Cantilever Beam

Energy dissipation takes place because of dynamic slip at the interface. For the given cantilever beam as shown in fig.3 frictional force at the interfaces per half-cycle of vibration is given by, consider length of the beam l, height 4h,pressure at a distance *x* is p(x) and normal load on the length of dx is p(x)bdx, where *b* is the width of the beam. Thus friction force is given asμp(x)bd(x), where μ is the coefficient of kinematic friction. Thus the energy loss due to the friction;

$$E_{loss} = \int_0^{\frac{\pi}{\omega_n}} \int_0^l \mu pb[\{\partial u_r(x,t)/\partial t\}dxdt \quad (14)$$

The energy introduced into the layered and jointed cantilever beam in the form of strain energy per half-cycle of vibration is given by

$$E_{ne} = \left(\frac{3E}{l^3}\right) y^2(l,0) \quad (15)$$

Where E = modulus of elasticity

I = cross-sectional moment of inertia,

= $b(4h)^3/12$

y = transverse deflection at the free end of the beam

By using above two equations, energy ratio is found to be;

$$\frac{E_{loss}}{E_{ne}} = \int_0^{\frac{\pi}{\omega_n}} \int_0^l [\mu pb\{\partial u_r(x,t)/\partial t\}dxdt]/[(3E/l^3)y^2(l,0)] \quad (16)$$

By making use of the boundary and initial conditions, energy ratio transform to;

$$\frac{E_{loss}}{E_{ne}} = [4\mu bhp\alpha y(l,0)]/[3(EI/l^3)y^2(l,0)] \quad (17)$$

Replacing

$$\frac{3EI}{l^3} = k$$

Where k = static bending stiffness of layered and riveted cantilever beam

Now the energy ratio can be written as;

$$\frac{E_{loss}}{E_{ne}} = \frac{[4\mu bhp\alpha]}{[ky(l,0)]} \quad (18)$$

G. Evaluation of Damping Ratio

The damping ratio is another way of measuring damping which shows the decay of oscillations in a system after a disturbance. When any system is disturbed from their static equilibrium position, they show oscillatory behaviour. Frictional losses damp the system and cause the oscillations to gradually decay to zero amplitude. In mathematical way it is expressed as the ratio of damping constant to the critical damping constant. The rate at which the motion decays in free vibration is controlled by the damping ratio ζ, which is a dimensionless measure of damping expressed as a percentage of critical damping.

H. Specific Damping Capacity (Ψ)

The damping capacity is defined as the energy dissipated per complete cycle of vibration. The energy dissipation per cycle is calculated from the damping force(f_d)and is expressed in the integral form as;

$$\Delta \cup = \oint f_d \, dx \quad (19)$$

The specific damping capacity (Ψ) is defined as the ratio of energy dissipated per cycle of vibration to the total energy of the system. If the initial (total) energy of the system is denoted by$\cup_{max}$,the specific damping capacity is given by;

$$\Psi = \frac{\Delta\cup}{\cup_{max}} \quad (20)$$

I. Loss Factor (η)

The loss factor η is the specific damping capacity per radian of the damping cycle and is widely used in case of visco-elastic damping. This is given as;

$$\eta = \frac{\Delta\cup}{2\pi\cup_{max}} \quad (21)$$

Where $\cup_{max}$is approximately equal to the maximum kinetic or potential energy of the system when the damping is low. It is also be given as;

$$\eta = \frac{\Psi}{2\pi} = \frac{\delta}{\pi} = 2\xi = \frac{\Delta\cup}{2\pi\cup_{max}} \quad (22)$$

III. EXPERIMENTAL SET-UP AND EXPERIMENTS

A. Preparation of the Specimens

An experimental set-up as shown in fig.5 has been fabricated to conduct the experiments. The test specimens of different sizes are prepared from the same stock of commercial aluminium alloy 5083 flats as presented in Table 3 Equi-spaced rivets of 4, 6, 8, 10 and 12 mm diameter are used to fabricate two-layer, three layer and four layer specimens with a constant clamping force. The distance between the consecutive rivets is so arranged that their influence zone just touches each other at the point of separation. For example, the centre distance between two consecutive rivets kept as 4.125times the diameter of the rivet. The length of the specimens has also been varied accordingly in order to accommodate different number of rivets.

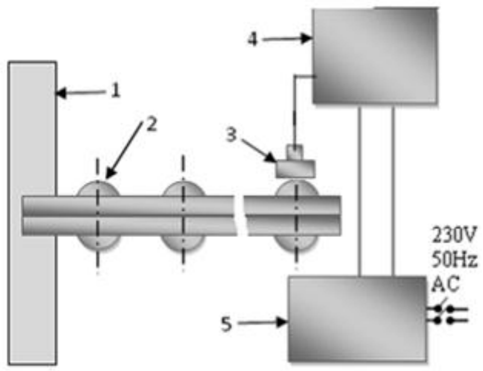

Fig. 5: Schematic diagram of experimental set-up
1-Fixed end, 2- Connected rivet, 3-Accelerometer, 4-Storage oscilloscope, 5-Distribution box

Property	Value
Brinell Hardness	75 HB
Ultimate Tensile Strength	315 Mpa
Proof Stress	125 Mpa
Fatigue Strength	159 Mpa
Elongation at Break	16%

Table 1: The mechanical properties of aluminium alloy 5083

Element	% Present
Magnesium (Mg)	4.00 - 4.90
Manganese (Mn)	0.40 - 1.00
Iron (Fe)	0.40 Typical
Titanium (Ti)	0.05 - 0.25
Chromium (Cr)	0.05 - 0.25
Silicon (Si)	0.0 - 0.40
Aluminium (Al)	Balance

Table 2: Chemical composition of aluminium alloy 5083

Thickness × Width (mm × mm)	No. of Layers	Types of Specimen	Length of Specimen Mm
(3+3) ×40	2	rivet jointed	420,450,480
(4+4) ×40	2	rivet jointed	420,450,480
(6+6) ×40	2	rivet jointed	420,450,480
(3+3+3) ×40	3	rivet jointed	420,450,480
(4+4+4) ×40	3	rivet jointed	420,450,480
(6+6+6) ×40	3	rivet jointed	420,450,480
(3+3+3+3) ×40	4	rivet jointed	420,450,480
(4+4+4+4) ×40	4	rivet jointed	420,450,480
(6+6+6+6) ×40	4	rivet jointed	420,450,480
6 × 40	2	solid	420,450,480
8 × 40	2	solid	420,450,480
12 × 40	2	solid	420,450,480

Table 3: Details of aluminium alloy specimens used for layered and jointed beams.

Fig. 6: Experimental set-up with the storage oscilloscope

B. *Experimentation*

In order to perform the experiments, the specimens are rigidly mounted to the support as discussed earlier. At first, the Young's modulus of elasticity and static bending stiffness are measured by carrying out static deflection tests. These measured values are subsequently used for the theoretical evaluation of logarithmic decrement of all the specimens. Later, the experimental logarithmic decrement is calculated from the time history curve of decaying signals. The detailed procedure to find out the above quantities is discussed in the succeeding sections.

1) *Measurement of Young's Modulus of Elasticity (E)*

The Young's modulus of elasticity (E) of the specimen material is found out by conducting static deflection tests. For this purpose, few samples of solid beams are selected from the same stock of aluminium flats. These specimens are mounted on the same experimental set-up rigidly so as to ensure perfect fixed boundary conditions as mentioned earlier. Static loads(W)are applied at the free end and the corresponding deflections (∇) arerecorded. The Young's modulus for the specimen material is then determined using the expression$E = \frac{WL^3}{3I\nabla}$, where L and I are the free length and moment of inertia of the cantilever specimen. The average of five readings is recorded from the tests from which the average value of Young's modulus for specimen (aluminium alloy) material is evaluated. Young's modulus of specimen materials (aluminium alloy) is 67.6Gpa.

2) *Measurement of Static Bending Stiffness (k)*

It is a well-known fact that the stiffness of a jointed beam is always less compared to an equivalent solid one. It means that the incorporation of joints to assemble layers of beams is accompanied by a decrease in the stiffness. The amount of reduction in the stiffness is quantified by a factor called stiffness ratio which is defined as the ratio of the stiffness of a jointed beam (k) to that of an identical solid one (k′). The stiffness ratio is inversely related to the number of layers used in the jointed specimen. Its exact assessment carries much significance in the theoretical evaluation of logarithmic decrement. The same static deflection tests as used in case of Young's modulus are performed to measure the actual stiffness (k) of a jointed specimen using the relation$= \frac{W}{\nabla}$.However, the stiffness of an identical solid cantilever beam is theoretically calculated from the expression$k' = \frac{3EI}{L^3}$.The average values of the stiffness ratio for two layered cantilever beams jointed with rivets has been calculated and presented in Table 4.

Thickness × Width mm× mm	Length of Spec-imen mm	Static Bending Stiffness		Stiffne-ss Ratio (k/k')
		Experim-ental k	Theor-etical k'	
(3+3)×40	420	1.8285	2.1447	0.8526
	450	1.3992	1.6108	0.8686
	480	1.1421	1.3165	0.8675
(4+4)×40	420	11.0862	12.7472	0.8697
	450	9.984	11.439	0.8728
	480	3.4364	3.922	0.8762

Table 4: Average stiffness ratio for two layered aluminium alloy beams jointed with rivet.

3) *Measurement of Damping (δ)*

The logarithmic damping decrement and natural frequency of vibration of all the specimens at their first mode of free vibration are found out experimentally. Different –different specimen as listed in the table 1, are taken for experiment. In order to excite the specimens at their free ends, a spring loaded exciter was used. The dial gauge is used with the exciter to recorded the initial amplitude of excitation. The amplitude of excitation was varied in steps and maintained as 0.1, 0.2, 0.3, 0.4, and 0.5 mm for all the specimens testing. The free vibration at the required amplitude of excitation was sensed with a non-contacting type of vibration pick-up and the corresponding signal was fed to a cathode ray oscilloscope through a digitizer to obtain a steady signal. The logarithmic damping decrement was then evaluated from the measured values of the amplitudes of the first cycle (a_1), last cycle (a_{n+1})and the number of cycles (n) of the steady signal by using the equation $\delta = \ln\left(\frac{x_0}{x_n}\right)/n$.The corresponding natural frequency was also determined from the time period (T_1)of the signal by using the relationship$f = \frac{1}{T_1}$.

Length ×Width × Height mm×mm× mm	Types of Specim-en	Stiffne-ss (k) N/mm	Damp-ing	% Decre-ase in Stiffness	% Incre-ase in Da-mping
450 × 40 ×(3+3)	rivet jointed	1.3992	0.01630	13.1363	130.878
450× 40 ×6	solid	1.6108	.00706		
450× 40 ×(4+4)	rivet jointed	9.9840	0.01482	12.7196	126.23
450× 40 × 8	solid	11.439	0.00565		

Table 5: Comparison of experimental logarithmic decrement and stiffness of identical solid and jointed beams (with 10 mm connecting rivets being excited at 0.5 mm).

IV. RESULTS AND DISCUSSION

The effect of the influencing parameters on the damping capacity of layered and jointed riveted structures is enumerated from experimental results as detailed below and the following discussion that have been made after analysing all the data.

A. *Effect of Diameter of Rivet*

The use of rivets of larger diameter increases the preload on the rivets, thereby increasing the normal force and the energy loss at the interfaces.

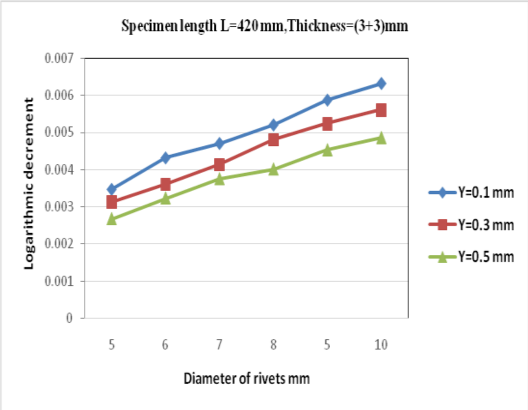

Fig. 7: Variation of logarithmic decrement with the diameter of rivet at different amplitudes of excitation (Y) for aluminium alloy specimen of cantilever beam having a thickness (3+3) mm.

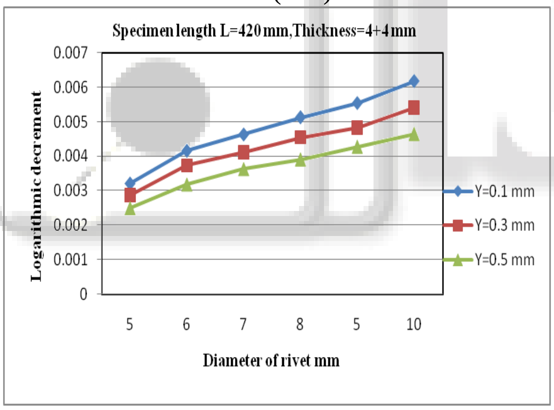

Fig. 8: Variation of logarithmic decrement with the diameter of rivet at different amplitudes of excitation (Y) for aluminium alloy specimen of cantilever beam having a thickness (4+4) mm.

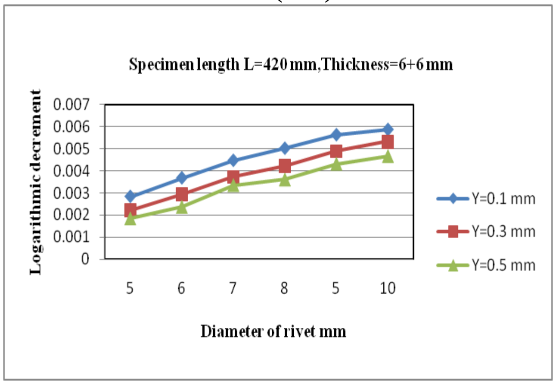

Fig. 9:Variation of logarithmic decrement with the diameter of rivet at different amplitudes of excitation (Y) for aluminium alloy specimen of cantilever beam having a thickness (6+6) mm.

B. *Effect of Number of Layers*

The thickness ratio of 1.0 yields maximum damping of jointed structures. This damping will further increase with the use of more number of layers compared to the solid beam of same overall thickness due to more friction interfaces which produces higher energy loss at the interfaces and gives higher damping.

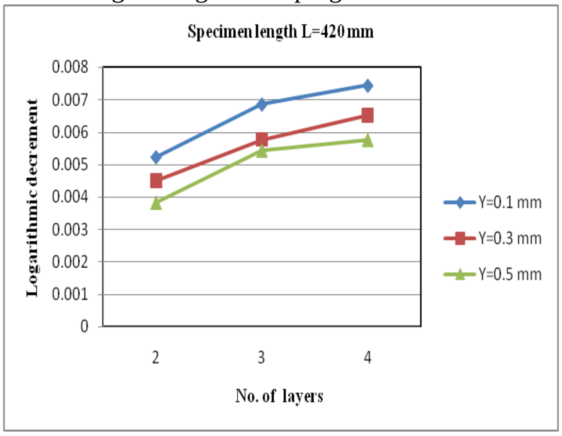

Fig. 10: Variation of logarithmic decrement with the number of layers for aluminum alloy specimens with beam length 420 mm, overall thickness 12 mm and rivet diameter 10 mm at different amplitudes of excitation (Y).

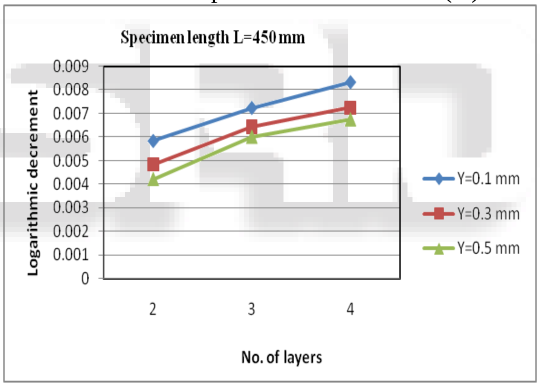

Fig. 11: Variation of logarithmic decrement with the number of layers for aluminium alloy specimens with beam length 450 mm, overall thickness 12 mm and rivet diameter 10 mm at different amplitudes of excitation (Y).

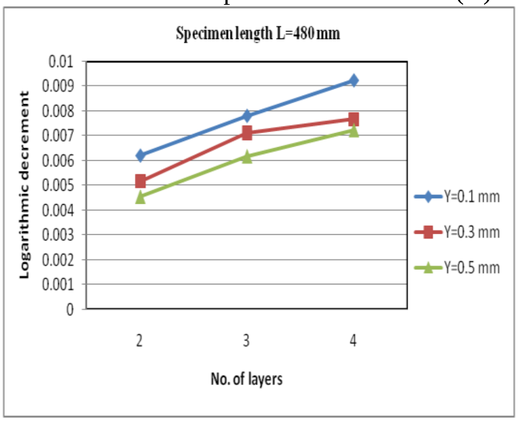

Fig. 12: Variation of logarithmic decrement with the number of layers for aluminium alloy specimens with beam length 480 mm, overall thickness 12 mm and rivet diameter 10 mm at different amplitudes of excitation (Y).

C. Effect of Length of Specimen

There is a reduction in the static bending stiffness with an increase in the length of the specimen so that the strain energy introduced into the system is decreased. As the longer specimens accommodate more number of rivets, there will be an increase in the overall dynamic slip, thereby causing more energy loss. The net effect of all these improves the damping with an increase in the length.

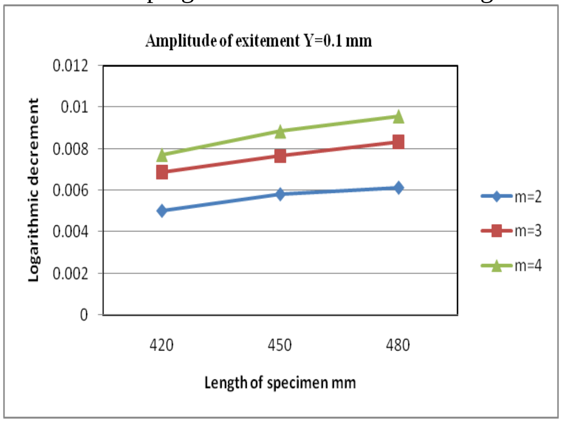

Fig. 13: Variation of logarithmic decrement with length of specimen with different no. of layers (m), overall thickness 12 mm and rivet diameter 10 mm at amplitude of excitation 0.1 mm.

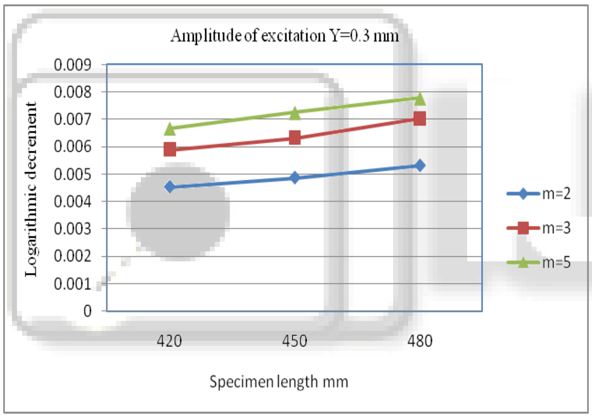

Fig. 14: Variation of logarithmic decrement with length of specimen with different no. of layers (m), overall thickness 12 mm and rivet diameter 10 mm at amplitude of excitation 0.3 mm.

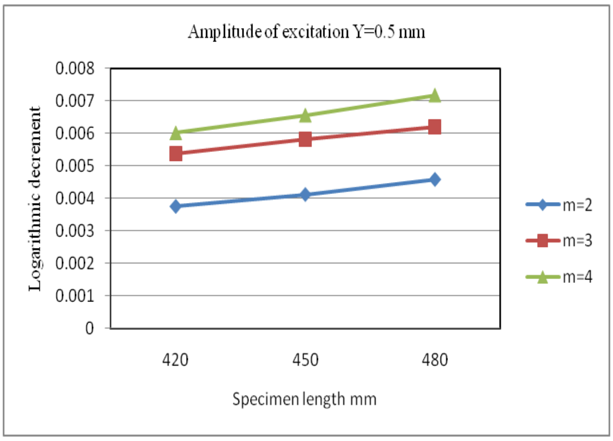

Fig. 15: Variation of logarithmic decrement with length of specimen with different no. of layers (m), overall thickness 12 mm and rivet diameter 10 mm at amplitude of excitation 0.5 mm.

D. Effect of Amplitude of Vibration

The increase in the amplitude of vibration results in more input strain energy to the system .It is found from the results that the energy loss occurs at a slower rate compared to the input strain energy. and hence as the amplitudes of excitation increases, there is a decrease in the logarithmic decrement.

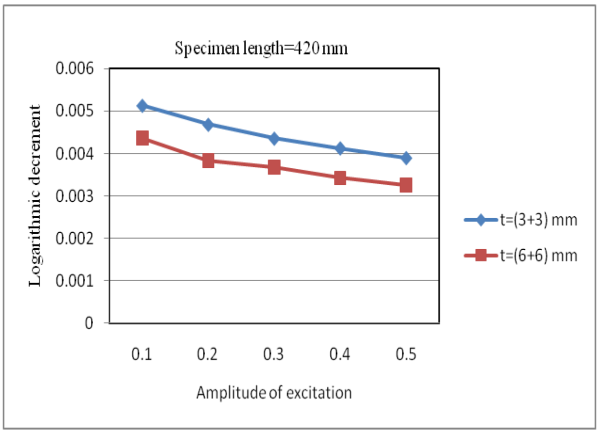

Fig. 16: Variation of logarithmic decrement with the amplitude of excitation with specimen length 420 mm and rivet diameter 10 mm having different beam thickness (t).

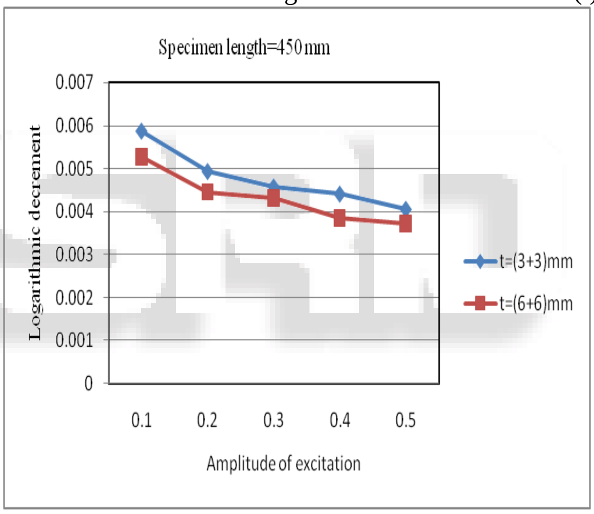

Fig.17.Variation of logarithmic decrement with the amplitude of excitation with specimen length 450 mm and rivet diameter 10 mm having different beam thickness (t)

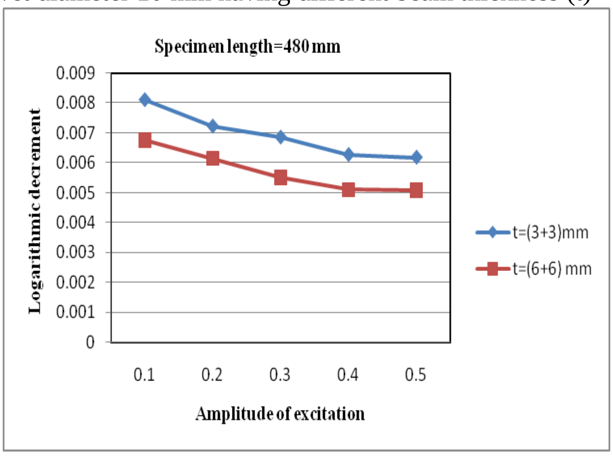

Fig. 18: Variation of logarithmic decrement with the amplitude of excitation with specimen length 480 mm and rivet diameter 10 mm having different beam thickness (t).

Length ×Width × Height mm×mm× mm	Influencing Parameter	Variation of Influencing Parameter	Variation in Logarithmic Decrement
450× 40 × (3+3) (amplitude of excitation Y=0.1 mm)	rivet diameter	increase from 8 to 10 mm	increase by 13.26 %
420× 40 × (3+3) (with 0.1 mm of excitation and 10 mm rivet diameter)	beam length	increases from 420 to 450 mm	Increase by 8.07 %
450× 40 × (3+3) (with 10 mm rivet diameter)	amplitude of vibration	increases from 0.1 to 0.5 mm	decrease by 30.72 %
450× 40 × (3+3) (with 10 mm rivet and 0.5 mm excitation)	number of layers	two layers	increase by130.88% compare to equivalent solid beam
		three layers	increases by 24.02% compared to that of two layers

Table 6: Effect of influencing parameters on the damping capacity with aluminium alloy

V. CONCLUSIONS

Mechanical joints and fasteners are primary sources of improving damping in structural design caused by friction and micro-slip between the interfaces. Due to the incorporation of joints in layered riveted beam, it is estimated that the damping capacity increases approximately by 125 to 130 % as compare to solid one, whereas their stiffness decreases by 15% to 22% only. In the present work, a mathematical analysis has been carried out to investigate the mechanism of slip damping in riveted structures.The present investigation will help the designers to estimate the damping capacity of the structures in order to maximize it as per the requirements in actual applications. Various variable has been examine for improving damping in rivet jointed structure are-

- Increasing the diameter of the rivets.
- Decreasing the initial amplitude of excitation.
- Increasing the cantilever beam length.
- Increasing the number of layers of the cantilevers.
- Decreasing the thickness ratio of the beam with constant overall thickness.

VI. FUTURE SCOPE

In the present investigation, the mechanism of damping and the various parameters affecting the damping capacity of layered and jointed riveted structures have been presented in detail to enable the engineers to design the structures depending upon their damping capacity in real applications. However, the present study can be extended for further research as given below-

- Study of damping may be studied for riveted structures consisting of layers of different materials.
- Present analysis can be extended for forced vibration conditions.
- The analysis can be extended to other boundary conditions such as fixed-fixed, fixed-supported etc.

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